

# LHC interaction region upgrade

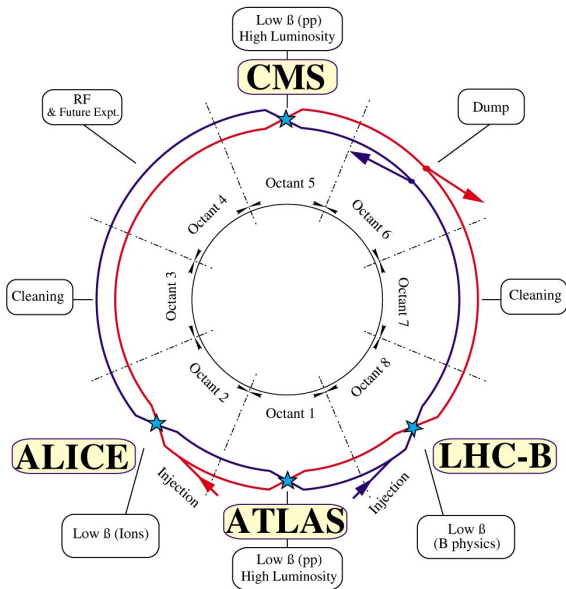
studies on dipole first and quadrupole first layouts

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# LHC layout



## LHC nominal performance

Quantity	Symb	Value	Unit
Collision energy	$E_p$	7000	[GeV]
Luminosity	$L$	$0.82 \cdot 10^{34}$	$[\text{cm}^{-2}\text{s}^{-1}]$
Number of protons per bunch	$N_b$	$1.15 \cdot 10^{11}$	$[\ ]$
Number of bunches	$n_b$	2808	$[\ ]$
Revolution frequency	$f_{\text{rev}}$	11.25	[kHz]
Bunch spacing	$t_b$	50	[ns]
RMS bunch length	$\sigma_z$	0.118	[m]
Normalized emittance	$\varepsilon_n$	$3.75 \cdot 10^{-06}$	[mrad]
Beta at the IP	$\beta^*$	0.55	[m]
RMS beam size at the IP	$\sigma^*$	$1.663 \cdot 10^{-05}$	[m]
Beam current	$I_b$	0.5818	[A]
Full crossing angle	$\phi_{\text{cross}}$	285	[urad]
Common pipe length	$l_{\text{sep}}$	90	[m]
Long-range parasitic collisions	$n_{\text{par}}$	12	$[\ ]$

# Luminosity

If  $R$  is the number of the events:

$$\frac{dR}{dt} = L\sigma \qquad [L] = [\text{cm}^{-2}\text{s}^{-1}]$$

where  $L$  is the luminosity and  $\sigma$  is the cross section of the event.  
The luminosity depends on the beam parameters by:

$$L = \frac{N_b^2 f n_b}{4\pi(\sigma^*)^2} F \qquad F = \frac{1}{\sqrt{1 + \left(\frac{\vartheta_c \sigma_z}{2\sigma^*}\right)^2}}$$

where  $\gamma$  is the relativistic factor,  $\sigma^*$  is the beta function at the interaction region,  $N_b$  is the number of proton per bunch,  $n_b$  is the number of bunches,  $\sigma^*$  is the beam size at the IP,  $F$  is the geometric loss factor.

The most important quantity is the integrated luminosity.

# LHC performance limitations

Some of the issues limiting the LHC performance are:

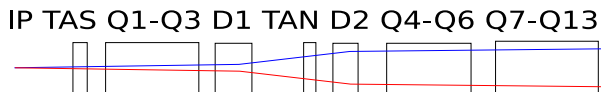
- ▶ peak field of the magnets;
- ▶ beam current (injector chain, the collective instabilities, the stored beam energy and radiation dose);
- ▶ Emittance growth (filamentation, noise);
- ▶ non-linear resonances driven by multipole errors (magnet, beam-beam kicks);
- ▶ beam-beam tune spread;
- ▶ e-clouds (heat and tune spread);
- ▶ cooling power and heat conduction;
- ▶ turn around time;
- ▶ Beta function at the IP (IR quadrupole apertures and gradients).

# Upgrade strategies

Some of the strategies for increasing the LHC luminosity are:

- ▶ implement a beam-beam compensation scheme (reduce beam-beam tune spread);
- ▶ increase beam current (shorten the bunches, increase their number);
- ▶ upgrade the injector chain (shorten the turn around time and increase reliability);
- ▶ upgrade the interaction region (decrease  $\beta^*$ ).

# LHC nominal layout



**TAS** Block the secondary particles generated in the IP;

**Q1-Q3** Triplet assembly made of common bore magnets which focus both beams;

**D1** Warm dipole, separates the beam;

**TAN** Block the neutral debris which pass through the quadrupoles;

**D2** Cold dipole which brings the beam trajectories parallel;

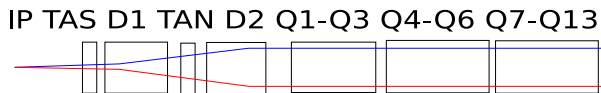
**Q4-Q6** Quadrupoles used for matching the arc;

**Q7-Q13** Pseudo arc cells used for matching the arc dispersion.

This layout is called quadrupole first.

The elements up to Q6 can be replaced for the upgrade.

## Dipole first triplet



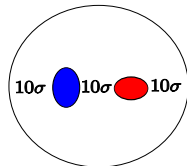
Another possible scheme is called dipole first where the triplet are 2-in-1 magnets and positioned after the D2.

The advantages are:

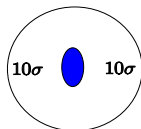
- ▶ reduced number of long range collisions,
- ▶ more efficient use of the quadrupole apertures since the crossing scheme is upstream,
- ▶ closed dispersion bumps when a crossing angle is present,
- ▶ possibilities for an individual correction scheme for the triplet multipole errors.

## Beam size

common bore



2-in-1 design



The region occupied by the beam is defined by the following specification:

- ▶ The beam orbit must be  $10\sigma$  far from the wall chamber,
- ▶ in case of a common beam pipe the two orbit must be separated by  $10\sigma$ ,
- ▶ tolerances for the beta-beat (20%) and close orbit and alignments error (7mm) must be included;

For a common bore layout:

$$d_a = 33\sigma + 7\text{mm}$$

For a 2-in-1 design:

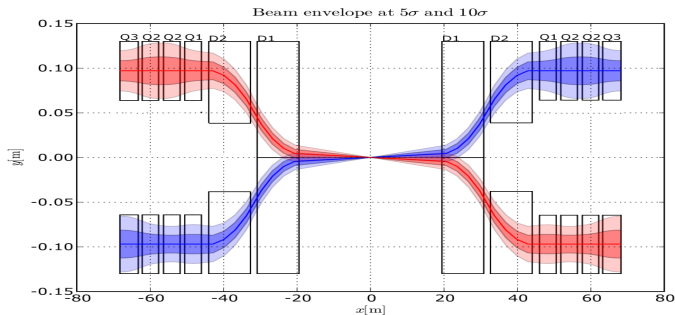
$$d_a = 22\sigma + 7\text{mm}$$

## Dipole first design directions

The guidelines followed for this design are:

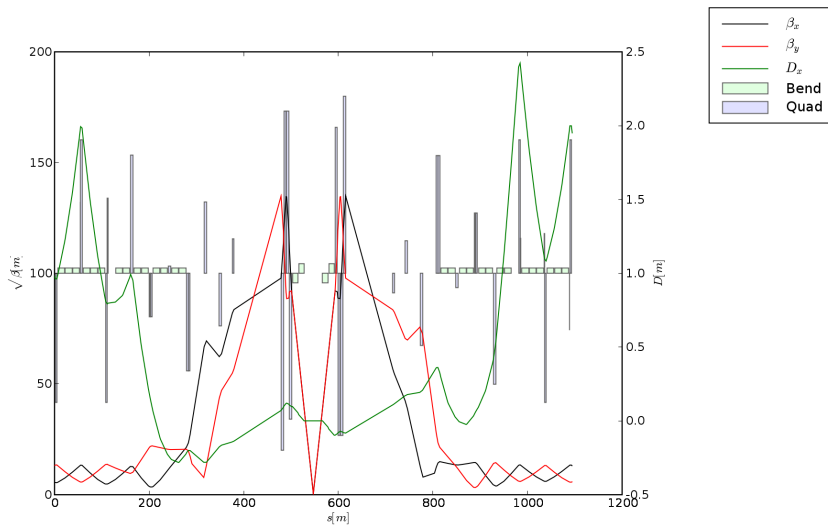
- ▶ leave the detector as it is;
- ▶ assume the Nb<sub>3</sub>Sn technology is available (15T peak field);
- ▶ assume that the TAS and the TAN can be embedded in D1-D2.

# Dipole first beam envelope and specifications



Mag.	Pos.	Length	Field	Inner D.
D1	19.45m	11.4m	15.0T	0.130m
D2	32.653m	11.4m	15.0T	0.080m
Q1	46.05m	4.5m	231.0T/m	0.080m
Q2A	51.87m	4.5m	-256.6T/m	0.080m
Q2B	57.69m	4.5m	-256.6T/m	0.080m
Q3	63.25m	5.0m	280.0T/m	0.080m

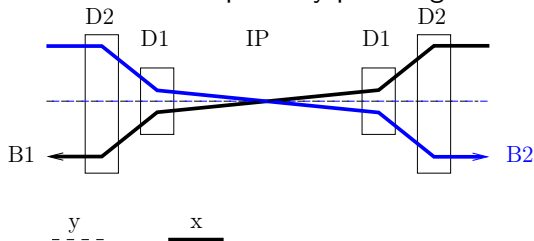
# Dipole first collision optics



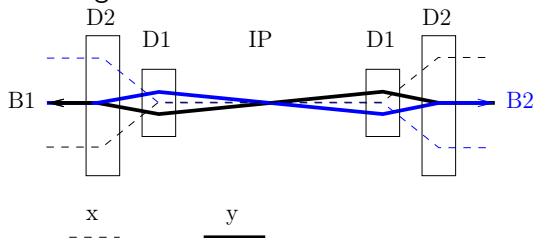
# Crossing angle schemes

Crossing angle is achieved:

- ▶ for the horizontal plane by powering differently D1 and D2



- ▶ for the vertical plane by tilting D1 and D2 resulting in a vertical deflection



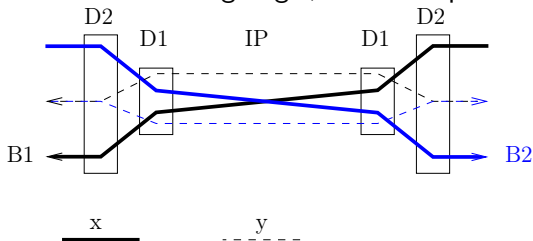
# Crossing angle schemes

Separation is achieved:

- ▶ or using the orbit correctors
- ▶ or dividing D1 and D2 in two part and powering them differently

Example for the last option:

- ▶ Horizontal crossing angle, vertical separation



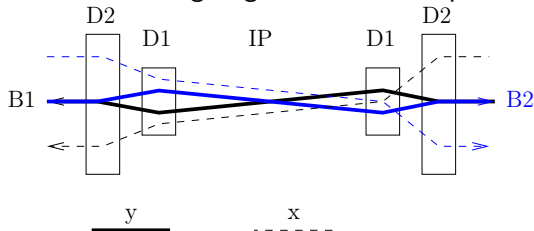
# Separation bump schemes

Separation is achieved:

- ▶ or using the orbit correctors
- ▶ or dividing D1 and D2 in two part and powering them differently

Example for the last option:

- ▶ Vertical crossing angle, horizontal separation

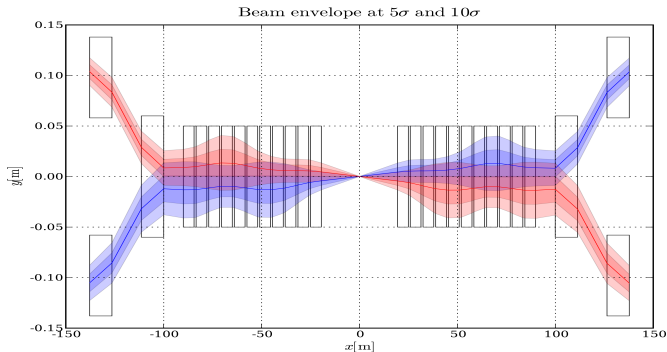


# Quadrupole first design directions

The guidelines followed for this design are:

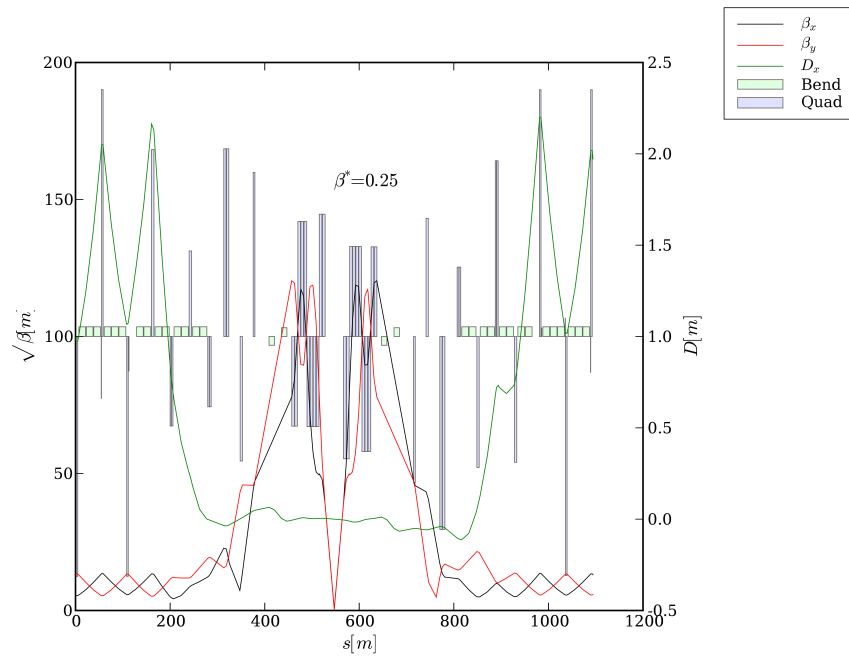
- ▶ leave the detector as it is;
- ▶ assume the Nb<sub>3</sub>Sn technology is not available (7T peak field);
- ▶ optimize the ratio between the required mechanical aperture and the available mechanical aperture to gain operational margins.

# Quadrupole first beam envelope and specifications



Mag.	Pos.	Length	Field	Inner D.
Q1	19.45m	5.5m (2)	104T/m	0.100m
Q2	32.45m	5.5m (4)	-76T/m	0.100m
Q3	58.45m	5.5m (3)	98T/m	0.100m
Q4	77.95m	5.5m (2)	-76T/m	0.100m
D1	100m	11.4m	7.0T	0.120m
D2	126m	11.4m	7.0T	0.080m

# Quadrupole first collision optics



# Dynamic Aperture and Field Quality Requirements

The dynamic aperture (DA) is estimated by tracking a particle distribution  $10^5$  turns in 60 realizations of the machine compatible with the error statistics.

The minimum of those 60 computed DAs should give the real dynamic aperture of the machine within a factor of 2 (see the LHC design report).

Therefore the aim is to find the maximum allowed multipole strength for a simulated DA of  $12\sigma$ .

At collision the DA is dominated by the field quality of the elements in the high  $\beta$  regions, that is:

- ▶ in the quadrupole first designs by the triplets quadrupoles;
- ▶ in the dipole first designs by the triplets and the separation/recombination dipoles.

# DA in the Dipole First Option

The parameter space for a strict specification of the field quality is too large to be explored systematically.

For a first estimation, the DA has been calculated including field errors only in the triplet.

The field errors of the rest of the machine should not have a big impact on the DA.

Including field errors of the sep./recom. makes difficult to extend the results to different layouts.

The parameter space has been probed by:

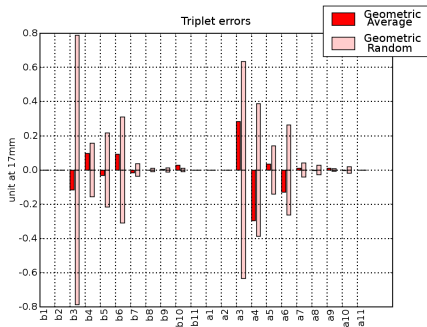
- ▶ using the field quality of existing magnets,
- ▶ using different scaling laws,
- ▶ using a multipole by multipole scan.

In the studies both IPs are in collision, no correction was applied and the beam-beam effect is not included.

# DA Results using Field Quality of Existing Magnets

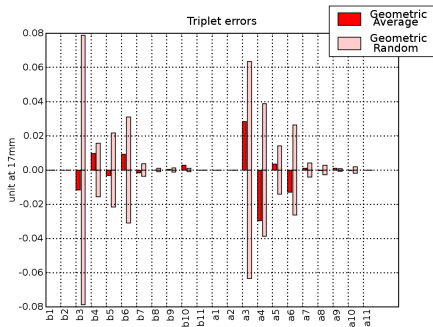
Using the field quality of:

► MQXB  
→  $DA = 3\sigma$ .



# DA Results using Field Quality of Existing Magnets

Using the field quality of:



► MQXB

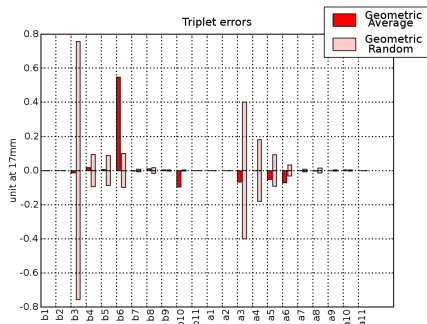
→  $DA = 3\sigma$ .

► 10% of MQXB

→  $DA = 8.3\sigma$ .

# DA Results using Field Quality of Existing Magnets

Using the field quality of:

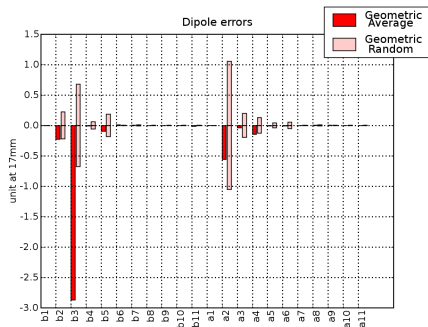


- ▶ MQXB  
→  $DA = 3\sigma$ .
- ▶ 10% of MQXB  
→  $DA = 8.3\sigma$ .
- ▶ MQY scaled [1] by  
 $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$   
→  $DA = 2\sigma$ .

[1] B.Bellesia, J.P. Koutchouk, E. Todesco. To be published.

# DA Results using Field Quality of Existing Magnets

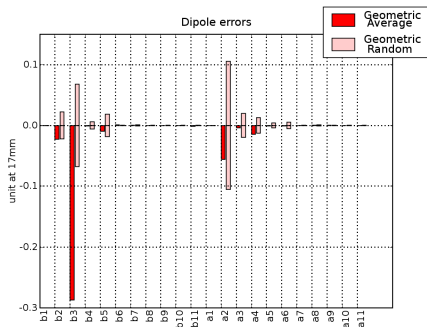
Using the field quality of:



- ▶ MQXB  
→  $DA = 3\sigma$ .
- ▶ 10% of MQXB  
→  $DA = 8.3\sigma$ .
- ▶ MQY scaled [1] by  
 $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$   
→  $DA = 2\sigma$ .
- ▶ MQXB and MBRCL  
→  $DA = 0.8\sigma$ .

# DA Results using Field Quality of Existing Magnets

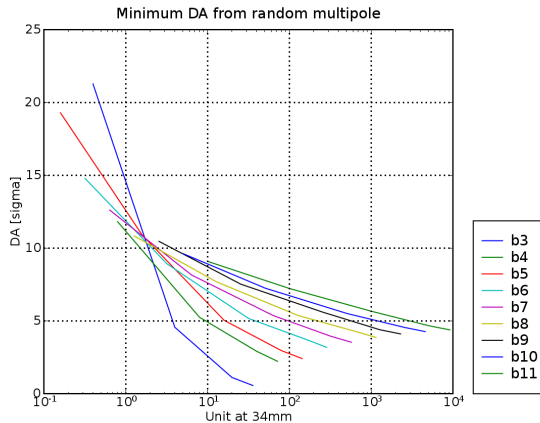
Using the field quality of:



- ▶ MQXB  
→  $DA = 3\sigma$ .
- ▶ 10% of MQXB  
→  $DA = 8.3\sigma$ .
- ▶ MQY scaled [1] by  
 $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$   
→  $DA = 2\sigma$ .
- ▶ MQXB and MBRCL  
→  $DA = 0.8\sigma$ .
- ▶ 10% of MQXB and MBRCL  
→  $DA = 6\sigma$ .

# DA Results using Single Multipole Scan

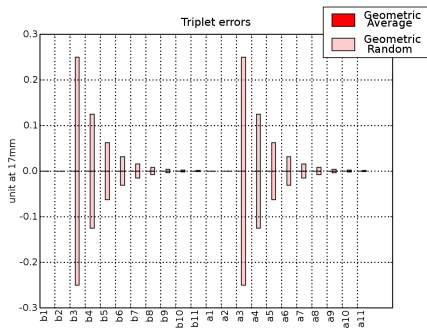
An upper bound on the minimum DA can be found by probing one multipole error at the time.



Taking all multipole together at 1 unit at 34mm...

# DA Results using Field Quality of Existing Magnets

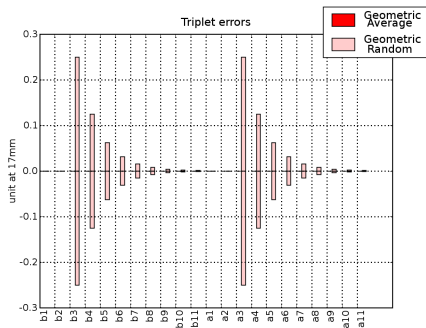
Using the field quality of:



- ▶ MQXB  
→  $DA = 3\sigma$ ,
- ▶ 10% of MQXB  
→  $DA = 8.3\sigma$ ,
- ▶ MQY scaled [1] by  $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$   
→  $DA = 2\sigma$ .
- ▶ MQXB and MBRCL  
→  $DA = 0.8\sigma$ ,
- ▶ 10% of MQXB and MBRCL  
→  $DA = 6\sigma$ ,
- ▶ 1 unit at 34mm  
→  $DA = 4.5\sigma$ .

# DA Results using Field Quality of Existing Magnets

Using the field quality of:



- ▶ MQXB  
→  $DA = 3\sigma$ ,
- ▶ 10% of MQXB  
→  $DA = 8.3\sigma$ ,
- ▶ MQY scaled [1] by  
 $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$   
→  $DA = 2\sigma$ .
- ▶ MQXB and MBRCL  
→  $DA = 0.8\sigma$ ,
- ▶ 10% of MQXB and MBRCL  
→  $DA = 6\sigma$ ,
- ▶ 1 unit at 34mm  
→  $DA = 4.5\sigma$ .
- ▶ Nominal LHC no correction  
→  $DA = 13\sigma$ .

## Beta-beat and chromaticity

$$Q = Q_0 + Q_1\delta + Q_2\frac{\delta^2}{2} + Q_3\frac{\delta^2}{2}$$

$$\frac{\Delta\beta}{\beta} = 1 + \Delta\beta_1\delta + \dots$$

The main source of  $Q_1$  is in the triplet.

The main source of  $Q_2$  is the beta-beat at the triplet.

The beat beat propagates at twice the betatron frequency, if the two IRs are phased by  $\pi/4$  the contribution cancel.

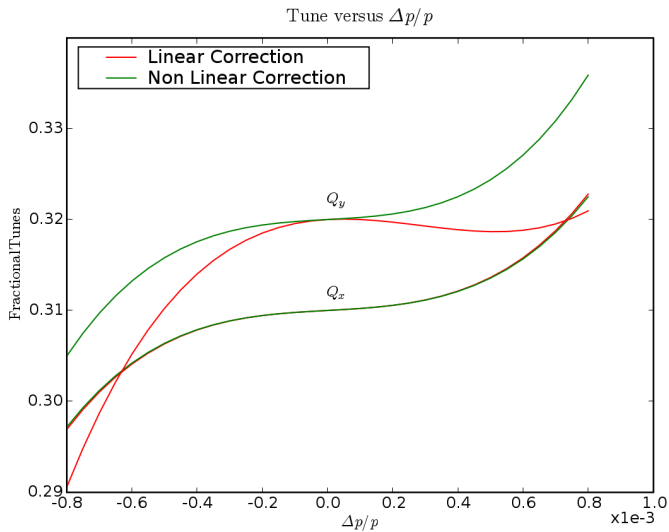
# LHC sextupole scheme

For each of the 8 arcs in the LHC there are:

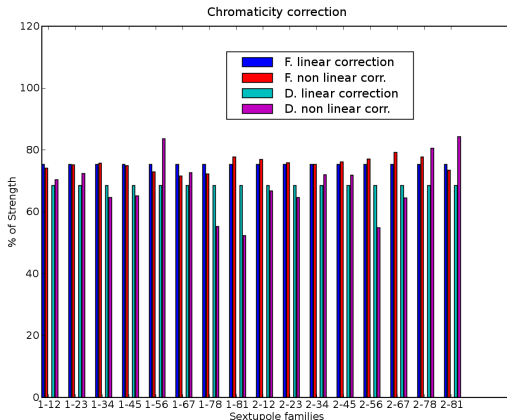
- ▶ two sext. families focusing ( $B_{\text{max}} = 1.280\text{T}$  at 17mm),
- ▶ two sext. families defocusing ( $B_{\text{max}} = 1.280\text{T}$  at 17mm),
- ▶ one sext. family of spool pieces ( $B_{\text{max}} = 0.471\text{T}$  at 17mm);

These elements can be used for correcting the first and second order chromaticity and the off-momentum beta-beat. They do not affect the long term stability as they are interleaved and at  $\pi$  phase advance.

# Chromaticity correction



# Corrector Strengths

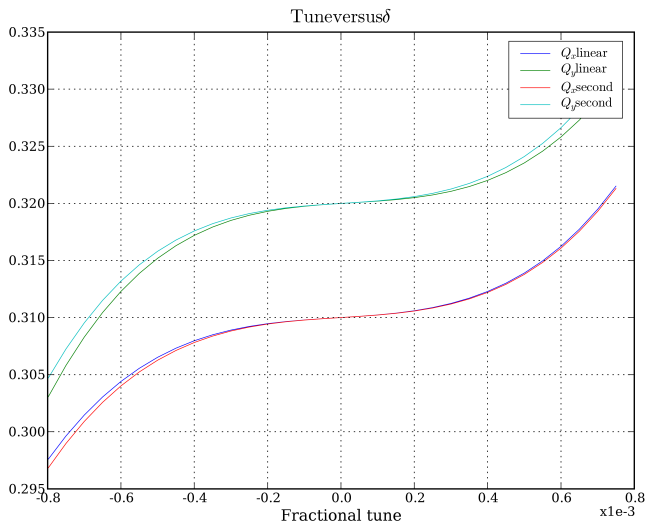


70% of the spool pieces are used in addition to the arc sextupole families.

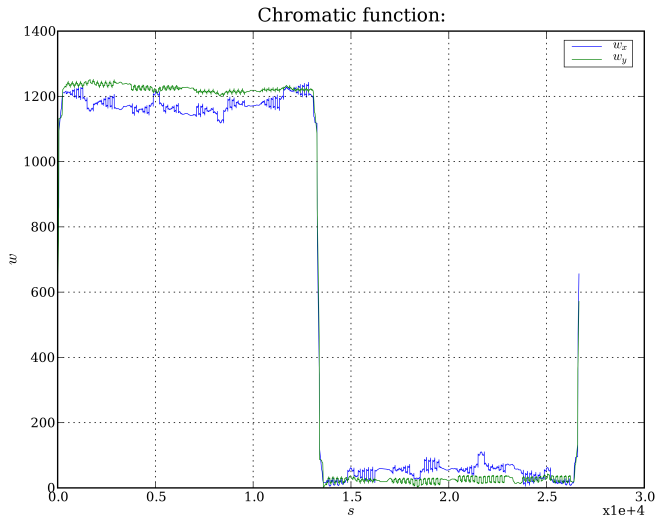
There is still budget for the beta-beat correction.

The present powering of the sextupole families cannot compensate third order chromaticity.

# Chromaticity correction



# Off momentum beta-beat wave



# Conclusion (1)

- ▶ A dipole first scenario, compatible with the Nb<sub>3</sub>Sn technology, has been developed;
- ▶ A quadrupole first scenario, compatible with the NbTi technology
- ▶ The required aperture is compatible with the element specifications;

## Conclusion (2)

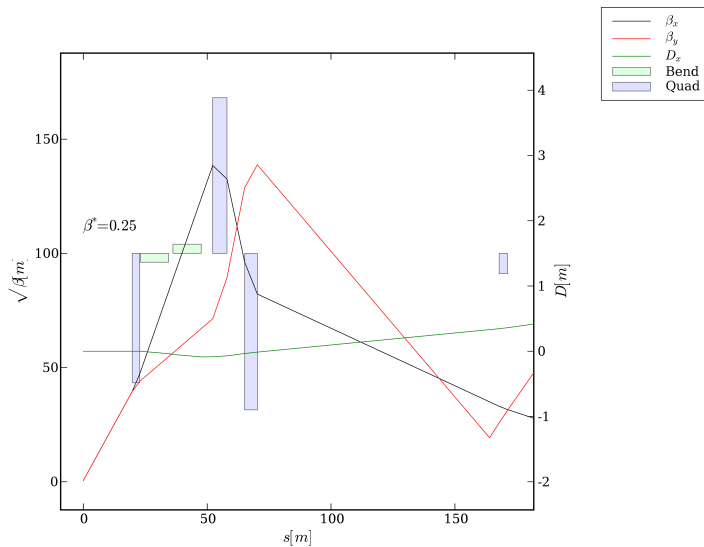
- ▶ The linear and second order chromaticity can be corrected by the sextupoles in the arcs.
- ▶ The third order chromaticity does not affect the beam in the bucket but it might be a limitation in operational margins (i.e. chromaticity measurement)
- ▶ The off-momentum beta-beat is low in the triplet but not in the arc. It is possible to position the beta wave in the half of the ring which does not include the betatron cleaning insertion (8% beta-beat allowed)

## Conclusion (3)

- ▶ The field quality of the present magnet production cannot assure alone the required DA.
- ▶ The better field quality expected from a large aperture does not help.
- ▶ b3 seems responsible for lowest DA but scales quickly. b6, b8, b10 scale slowly and might represent a bottle neck.
- ▶ The multipole errors should be smaller than 1 unit at 34mm for upgrade scenarios where beta-max is larger than 18km.
- ▶ An effective corrector package is needed to reach the required DA.

## Further Studies for the dipole first layout

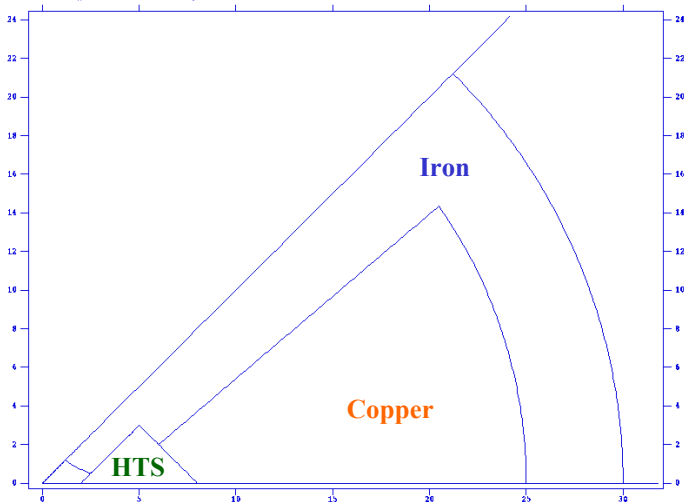
- ▶ the heat load and the radiation damage due the debris has not been addressed so far;
- ▶ it is not clear how to cope with neutral debris and the D2 design.
- ▶ the D1 can act possibly as a magnetic TAS (open midplane design) for the charged debris but it is not protected from the debris crossing its face;
- ▶ it is under study a TAS with a HTS superferric quadrupole (Ramesh Gubta idea) which should be able to protect the downstream magnet and reduce the beta max in the triplet.



# 1/8 Model of the HTS Quad Embedded in TAS

(HTS coils remove a large amount of heat at 20 K)

LARP TAS HTS Quad 34 mm: Desired gradient 230 T/meter at 20 K



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## Further Studies for the quadrupole first layout

- ▶ the heat load and the radiation damage due the debris has not been addressed so far;
- ▶ the optics can be further optimized
- ▶ maybe an hybrid scheme (point-to-parallel common bore, separation dipole, parallel-to-point 2-in-1 design) can reduce the beta max (Dejan Trbojevic idea);
- ▶ thick lens IR design is an hard problem: fuzzy boundary conditions, many isolated local minima. A systematic exploration of the solution space using selected monodimensional tracks can be beneficial (Steve Peggs idea) for a better understanding of the problem.

... the end.

Thanks for your attention.